

A New Proton Fluence Model for $E > 10$ MeVJ. Feynman⁽¹⁾, T. P. Armstrong⁽²⁾, L. Dao-Gibner⁽³⁾, S. Silverman⁽⁴⁾

Abstract:

We describe a new engineering model for the fluence of protons with energies > 10 MeV. The data set used is a combination of observations made primarily from the Earth's surface between 1956 and 1963 and observations made from spacecraft in the vicinity of Earth between 1963 and 1985. With this data set we find that the distinction between "ordinary proton events" and "anomalously large proton events" made in earlier work disappears. The > 10 MeV fluences at 1 AU calculated with the new model are about twice those expected on the basis of models now in use. In contrast to earlier models, our results do not depend critically on the fluence from any one event.

Introduction:

The proton fluence model currently used to evaluate hazards to spacecraft systems is that developed by King in 1974. That model was designed specifically to predict fluence during the period from 1977-1983, i.e. the 21st solar cycle.

Because of this specificity we undertook a review of the King model and as a result of the review, we have developed an updated model for energies > 10 MeV. The model is now being extended to $E > 30$ MeV. The purpose of this paper is to provide the workshop with an overview of our approach to this problem. We can not report on our work in full detail because of time and space limitations of the workshop and this paper gives only a brief outline of the work.

The King (1974) model for 1977-1983 was based on two assumptions. First King noted that the fluence during the solar cycle that maximized in 1957 (cycle 19, maximum annual sunspot number 190) was much larger than the fluence during the 20th cycle that had just been completed. The fluence during cycle 20 was dominated by a single event, the great proton flare of August, 1972. This lower fluence during cycle 20 (maximum annual sunspot number 107) was in agreement with the notion that was widely held at the time, i.e. that the number of great proton flares during a solar cycle was a function of the cycle's maximum sunspot number. Furthermore, the predictions King used for sunspot maximum for cycle 21 indicated that it would resemble or be smaller than cycle 20. With these assumptions about the relation between sunspot number and major proton flares and about the intensity of cycle 21 it was very reasonable to use the cycle 20 data base to make a conservative prediction of cycle 21 fluence. However, neither of these assumptions have proved valid for cycle 21. There were no major proton events at all during cycle 21 despite the fact that the maximum annual sunspot number in cycle 21 was 155, compared to cycle 20's maximum of about 107. The failure of these assumptions indicates the importance of reviewing the data and producing a new model.

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Data Base

Data on proton fluences come from two major sources. Since 1963 instruments have been observing proton fluxes in space. All of the feasible data from satellite observations have been collected and edited for valid solar particle responses. A nearly time continuous record of daily average fluxes of particles above the thresholds of 10, 30 and 60 MeV has been constructed. The details of the production of this data set are described in Armstrong et al., (1983). These data form one of the two sets used. The second data set is that used by Yucker (1970, 1971) and consists of the events between 1956 and 1962. As is well known, several of these earlier events were said to have fluences comparable to and even larger than the event of August 1972. Because these events occurred before the space era had really begun, and because they were not observed from interplanetary space, it is widely believed that the fluences reported for them were highly inaccurate and exaggerated. To check on the validity of this data set, a careful review of the original papers was undertaken. The care with which these early events were studied can be illustrated by noting that a conference was held on the November 1960 solar-terrestrial events at the then Air Force Cambridge Research Laboratories (now known as the Air Force Geophysics Laboratory). Twelve papers were given at the conference and a 165 page report was produced (Aarons and Silverman, 1962). A second thorough review of the known high fluence events between 1949 and 1961 was reported on in the Solar Proton Manual edited by Frank McDonald (1982). In that publication Malitson and Webber (1962) report that events since 1956 had been carefully studied and 1956 was chosen here as the beginning of our data set. Malitson and Webber reviewed their data in the Solar Proton manual as did Fichtel, Guss and Ogilvie in the next paper in the manual. Fichtel et al, (1962) had as their goal to determine the fluences of individual solar particle events within a factor of two. Fichtel et al. claim that the accuracy obtained is frequently much better. We concluded that the accuracy of the pre-1963 data was good and the data should be included in the new proton fluence model. As a non-scientific aside we would like to mention that the fact that these events were extremely large is not doubted by those observers who are still active in the field and who were concerned with proton events and aurora at the time they occurred. This includes two of the authors of this paper and several of the attendees at this workshop. On the basis of our reviews of the 1956-1962 data set we have included that data in our data base.

Method of Analysis

To analyze the data we followed the general approach used earlier by Yucker (1971) and King (1974). That is, we first studied the distribution of event magnitudes. Malitson and Webber (1962) had stressed that solar flares producing protons occur in groups with several flares occurring over a period of days in the same active center. Since these grouped events can not be assumed to be occurring independently of one another the distribution of fluences in a data set that considers each flare to be a separate event can not be expected to be a random sample of any underlying parent population. We therefore decided to integrate over each group of flares in our definition of "event fluence." Initially we were concerned that there would be a certain amount of arbitrariness in choosing the beginning and end times of events. To check this, beginning and ending times for events were chosen independently by two of the authors (J. F and LDG) but no significant differences were found between the two resulting lists.

Using the event fluences determined in this way we tested to see if the fluences followed a log normal distribution. The events were ordered according to the log of the magnitude and this was plotted vs. the percent of observed events that have a magnitude less than the given event. To be more exact fluences were plotted against $(i \times 100)/(n+1)$ where i is the rank value of the events ordered from smallest to largest and n is total number of events used in the data set. The graph paper used to plot the results is ruled so that a log normal distribution will appear as a straight line. The result for the $E > 10$ MeV data set is shown in Figure 1. Most of the data lies on a straight line. For the lowest fluences shown, the data turns up and the observed fluences become much larger than those expected from any straight line. This is an artifact and is expected whenever a data set is truncated (Nelson, 1982). In our case we have included only those events for which the fluence was greater than 1×10^7 particles/cm².

The data for fluences above 2×10^7 particles/cm² is well fit by a straight line. This is in contrast to King's (1974) results where only the data from cycle 20 was considered (for the reasons discussed in the introduction). In that case the 1972 event was so much larger than any other event in the set that it could not be considered part of the same distribution. King had to treat the 1972 event separately from other events. He called the 1972 event an AL (anomalously large) event and all other events OR (ordinary). In the present study the 1972 event is not outstanding and, in fact is not the event with highest fluence. These results for the $E > 19$ MeV data encourage us to use a single method of analysis for all events in the data set.

Solar Cycle Variation

In King's treatment he distinguished between the maximum and minimum phases of the sunspot cycle. However, "maximum and minimum" phases were not clearly defined. This would have caused difficulty if the 1972 event was to have been predicted. The maximum of cycle 20 occurred in 1968. Thus the event occurred four years after solar maximum and 3 years before solar minimum. If a prediction was to have been made from say 1965, would the appropriate model have been considered to be the maximum or minimum model?

In order to examine the solar cycle dependence in more detail, we used a superposed epoch analysis of the annual fluence for the 30 years covered by our data set. Our approach differed from that of other workers in that we defined the time of cycle maximum accurately to 0.1 years instead of the usual 1 year accuracy. The times of maximum of the 13 months running average sunspot number were supplied by Heckman (Gary Heckman, personal communication). The "years" of the cycle were then also defined as 365 day periods centered on the sunspot maximum correct to 0.1 years, i.e., "years" are not calendar years.

The result of this analysis for $E > 30$ MeV and for the 3 cycles for which we have data is shown in Figure 2. Notice the clear difference between the 7 years of high fluence and the 4 years of low fluence in each cycle. With only two exceptions, the annual fluences exceeded 10^8 particles/cm² during the 3 sets of 7 hazardous years/cycle and were less than that during the other 3 sets of 4 years/cycle. This is true even if no major proton events occurred during a hazardous year of a particular cycle. Furthermore, note that the hazardous period is not centered on sunspot maximum but extends from 2 years before maximum to 4 years after maximum.

This clear result has important implications to space missions. In comparing the fluences to be expected during different missions it is very important to take into account the actual launch date, since we can now be quite secure in predicting negligible fluences during the 4 minimum years of each cycle. Also notice that the dates of the last three cycle maxima occurred 11 years apart to the 0.1 year, so that we can be reasonably confident in predicting the time of the next maximum (about 1991). There is much more variance in the time between minima. The first spots of the new cycle (22) have appeared during the last 6 months (H. H. Sargent, personal communication, 1987).

Solar Cycle Corrected Proton Fluences

With the establishment of such a clear solar cycle variation, the approach to the determination of the best fit to the fluence distribution must be changed somewhat. The distribution should be constructed using data from only the 7 hazardous years in each cycle. The few small events that occurred during the 4 year quiet periods should be dropped from the data set.

The hazardous years' fluence distribution for protons with $E > 10$ MeV is shown in Figure 3. Again there is a turnup of the points at low fluence due to truncation of the data set. However, even after this is taken into account the rest of the data do not define a single straight line. We have also looked at other types of distribution functions such as type II and III extreme value distributions but the fits to the data were not improved. Our approach to the problem of the non-linearity of the data is to note that it is only those events with large fluences that influence the total fluence during a year. It is therefore more important to fit the large fluence part of the distribution than the low fluence part. We have carried out our analysis using the straight line eyeball fit shown in Figure 3. The turnup of the data at low fluences is an artifact due to the truncation of the data set (Nelson, 1982) and these points are not taken into account in the fit. Note that this fit does not depend crucially on the accuracy of the determination of the fluence from any one event. This is an advantage when compared with the situation faced by King who had to use fluences from only one solar cycle during which there was only a single event with fluences greater than 2×10^{10} particles/cm² for $E > 10$ MeV.

Statistical analyses

Since the high fluence portion of the data can be fit quite well with a straight line, the analysis was carried out along the lines used by King for the so called "ordinary flares." Let f_p be the proton fluence of an event, f_p can be written as $f_p = 10^F$. If f_p is distributed lognormally then F is distributed normally and its density function is commonly expressed as

$$f(F) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2} \left(\frac{F-\mu}{\sigma} \right)^2} \quad (1)$$

where σ is standard deviation, and μ is the mean log fluence. These are obtained from the straight line fit to the data. The probability that during a mission length τ the fluence level will exceed f_p is

$$P(>F, \tau) = \sum_{n=1}^{\infty} p(n, w\tau) Q(F, n) \quad (2)$$

where

$p(n, w\tau)$ is the probability of n event(s) occurring during mission length τ if an average of w events occurred per year during the observation period. The probability is assumed to follow a Poisson distribution and is calculated as

$$p(n, w\tau) = e^{-w\tau} \frac{(w\tau)^n}{n!} \quad (3)$$

This choice of occurrence distribution is somewhat different from that of King who used an extension of the Poisson method introduced by Burrell (1971) to account for the small size of the sample of events available to King. Since our sample consists of over 50 events, we have not used the Burrell extension.

$Q(F, n)$ is the probability that the sum of all fluences due to n events will exceed 10^F . $Q(F, 1)$ is the probability that the fluence given by that 1 event which occurred is greater than or equal to 10^F . $Q(F, 2)$ is the probability that 2 events occurred and the sum of their fluences is greater than or equal to 10^F . $Q(F, 3)$ etc....

The values of $Q(F, n)$ are simulated using a Monte Carlo method. The Monte Carlo program utilizes two subroutines given in Press et al. (1986). One is a random number subroutine which generates random numbers with a uniform distribution in the interval of $[0, 1]$. The other is a subroutine which applies the Box-Muller method of inverse transformation to obtain a Gaussian distribution. The inverse transformed method is discussed in detail in Yost, (1985).

The random numbers are assumed to be the inverse function of $p(F)$ which is defined as:

$$p(F) = \int_{-\infty}^F \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2} \left(\frac{F - \mu}{\sigma} \right)^2} dF^* \quad (4)$$

which can be written as

$$p(F) = \int_{-\infty}^z \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2} t^2} dt \quad (5)$$

where $z = \frac{F-\mu}{\sigma}$

The values of μ and σ used in equation 4 are those obtained from the straight line fit to the log fluence F distribution. As explained above since the larger fluence events were very important in calculating the total expected fluences, the largest events were given greater weight than the small fluence events in determining the fitted straight line. Generating these random numbers and performing the inverse transformed calculations on them will result a set of numbers that are random samples of the fit to the log fluence F distribution.

The actual simulation of $Q(F,n)$ consists basically of two steps. In step one, N sets of random samples from a Gaussian distribution are generated. N is a large number to ensure the randomness (100000). Each set j is a collection of n random numbers x_i . In step two, each set j is assigned a value of 1 if

$$\sum_{i=1}^n \left(10^{x_i * \sigma + \mu} \right) \geq 10^F \quad (6)$$

The ratio of the cumulative numbers of set j with value of 1 over the total numbers of generated sets N is the probability of exceeding fluence f_p due to n event(s). This procedure is repeated to determine the value of each $Q(F,n)$ of interest.

Equation (2) has been evaluated for various mission lengths τ and the result is shown in Figure (4).

Results

The procedure described above has been carried out for the active years of the solar cycle and for various mission lengths. Figure 4 shows the results for energies >10 MeV. This figure gives the probability of exceeding a given fluence level over the life of the mission assuming constant heliocentric distance = 1AU. For estimates of fluence at other heliocentric distances a correction must be made for the radial dependence of fluences. This problem is discussed in the report of the solar cosmic ray working group in this proceedings. Figure 4 shows five mission lengths. In calculating mission length only the time that the spacecraft spends in interplanetary space during solar cycle active years should be included.

In Table 1 we compare our new expected fluences with the King value for a mission length of 2 years. The new fluences are about twice the King fluences at energies >10 MeV. The "confidence levels" should be interpreted as meaning that, if 1,000 two year missions were flown at different times during solar cycle active years then 800 of them (or 950 depending on the chosen "confidence level") would have fluences no larger than the fluences shown in the table. (Of course it would take more than 2,000 years to carry out such a statistical study.) The "confidence level" does not include changes that would come about from using slightly different fits to the observed distribution of event fluences in Figure 3.

Energies with lower bounds greater than 30 MeV have not yet been treated in the new model. Until that work is carried out we suggest using the 10 MeV results and extrapolating to higher energy using the 1972 event as a model. This method of dealing with energies >10 MeV (including >60 MeV and >100 MeV) is unsatisfactory and the new work needed to extend the model properly should be undertaken.

Recommendations

As part of this workshop we have been asked to suggest future work to improve the models.

For protons at 1 AU and for energies >10 MeV studies of long term variations in occurrence frequency of major proton events may result in more secure estimates of the number expected in the future. There is some evidence that the occurrence frequency of major proton events changes with the 88 year cycle and this issue requires further study. The question of where we now are in the 88 year cycle should also be studied (Feynman and Fougere, 1985, Feynman and Silverman, 1987). A second opportunity for improvement may exist in the use of more sophisticated statistical methods. We also suggest that the proton flux model be looked at to see if the incorporation of new more extensive data would improve that model.

Several problems exist in extending proton models to regions other than 1 AU. We are very uncertain as to the radial dependence of proton fluences, especially for major events in which perhaps the fluences and certainly the maximum fluxes are influenced by shocks and other disturbances in the solar wind. The effects of interplanetary propagation on major events should be studied.

Very little observational or theoretical information is known for energies less than 10 MeV. There are at least 2 sources of particles at these energies. One is the low energy tail of the solar particle events and the other is particles accelerated out of the solar wind by shocks. Both sources should be incorporated into proton fluence models if we are to prevent both over or under design.

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Table 1. 2 Year Mission ($E > 10$ MeV)

Confidence Level, %	King	New
80	1.3×10^{10}	2.5×10^{10}
95	4.0×10^{10}	7.7×10^{10}

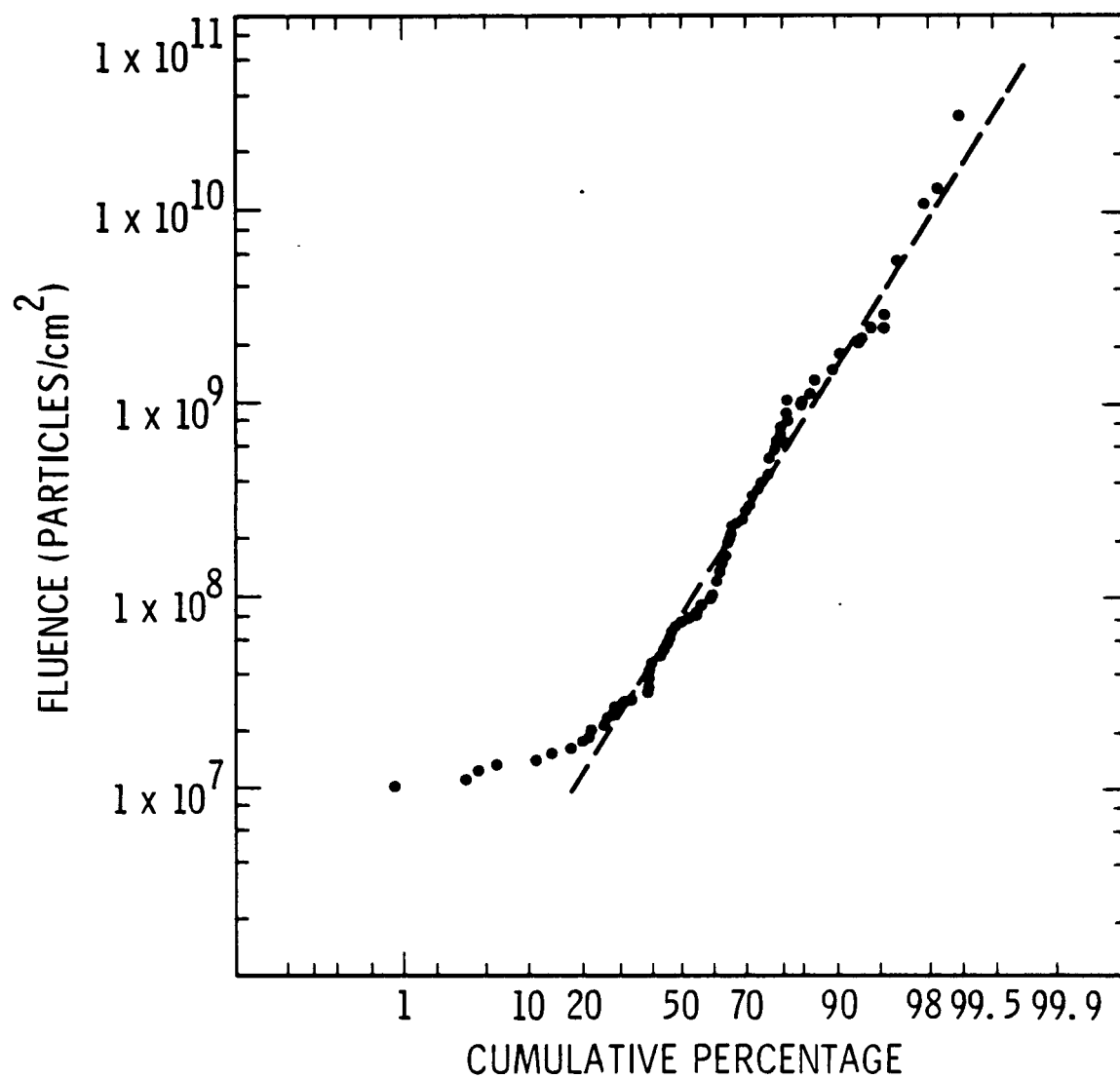


Fig 1 Distribution of fluences for complete data set, 1956-1986, for proton energies >10 MeV.

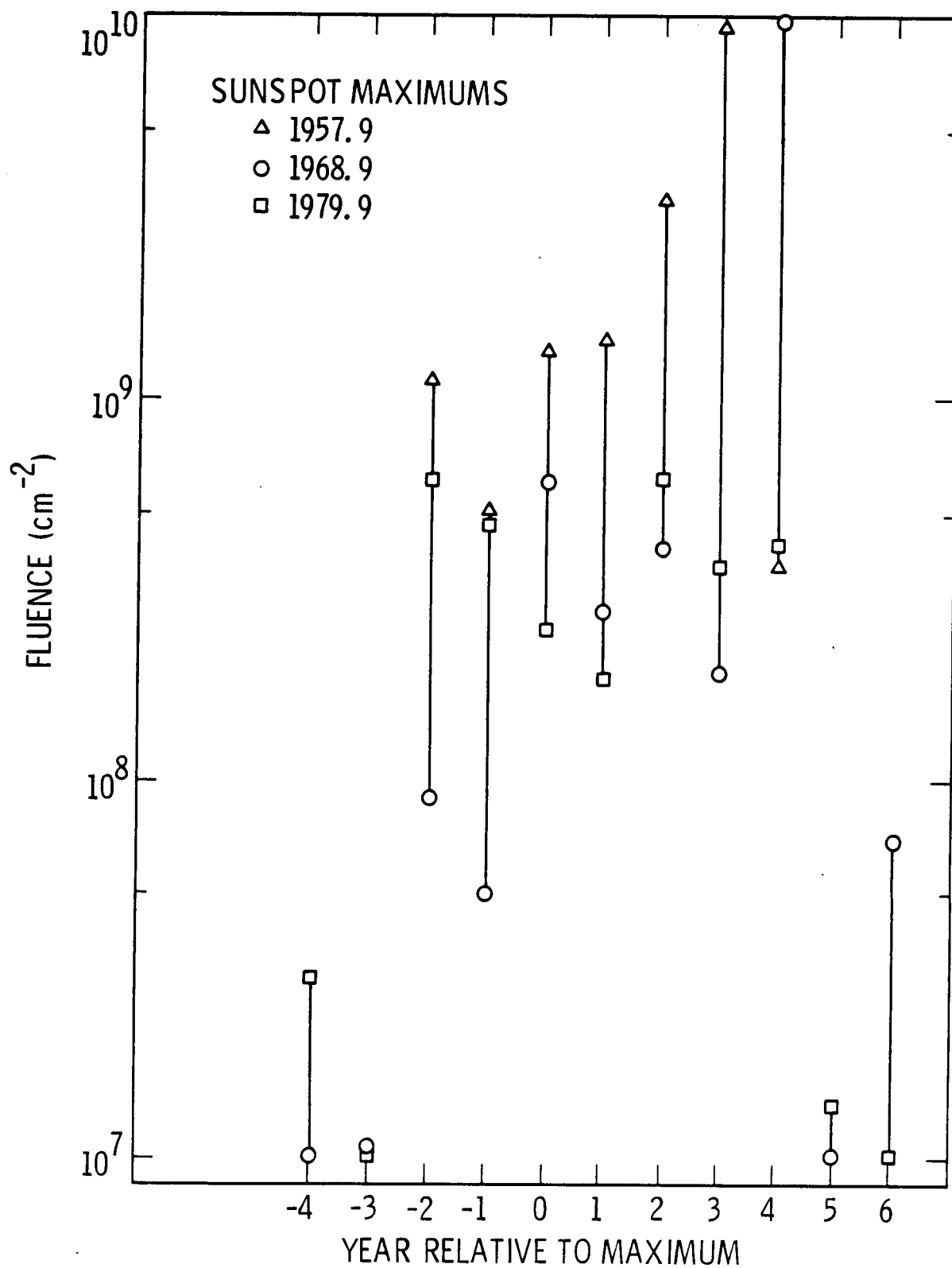


Fig 2 Solar cycle dependence of annual fluences, 1956-1986. See text for definition of "years".

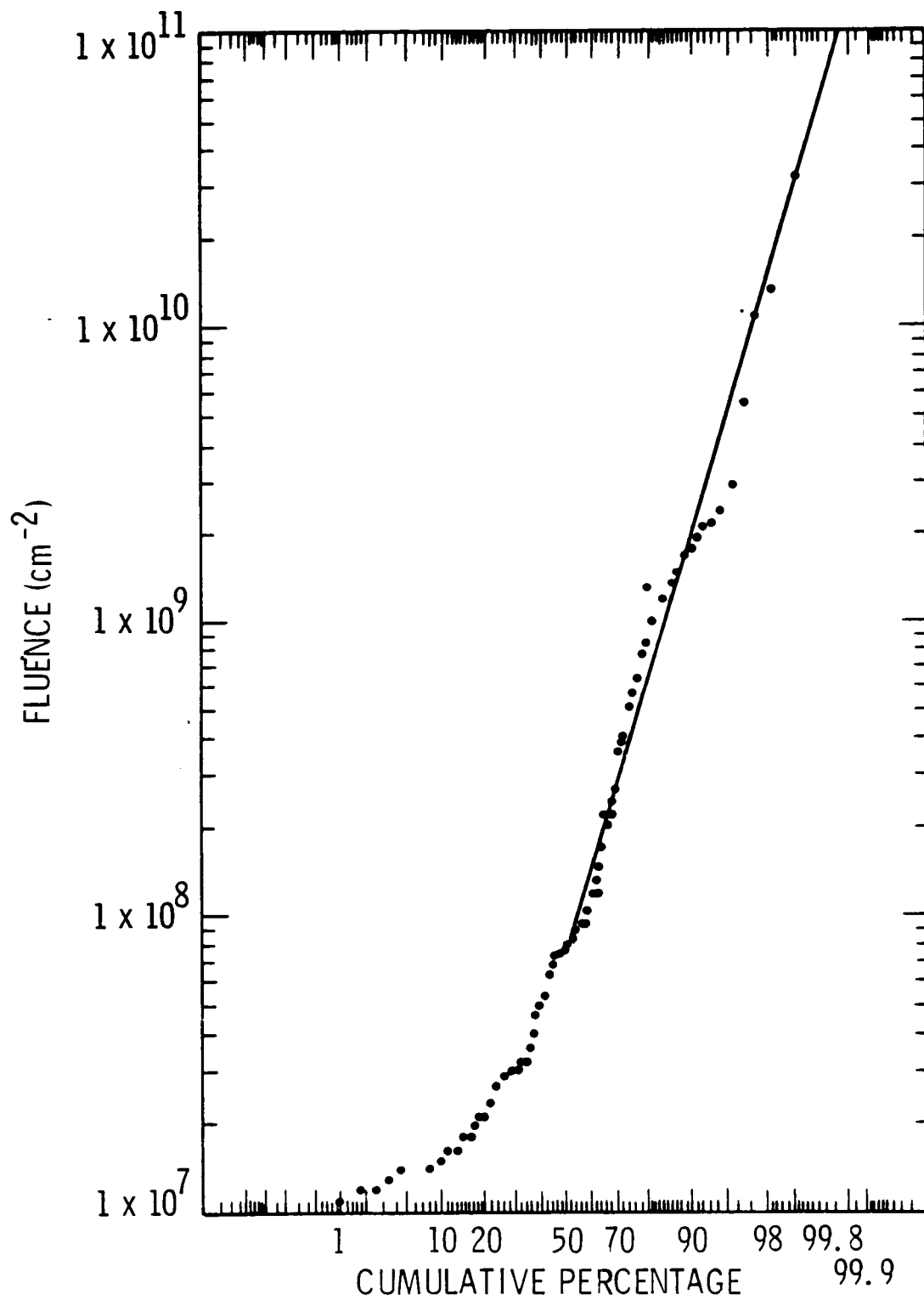


Fig 3 Distribution of fluences for solar cycle active years for proton energies >10 MeV.

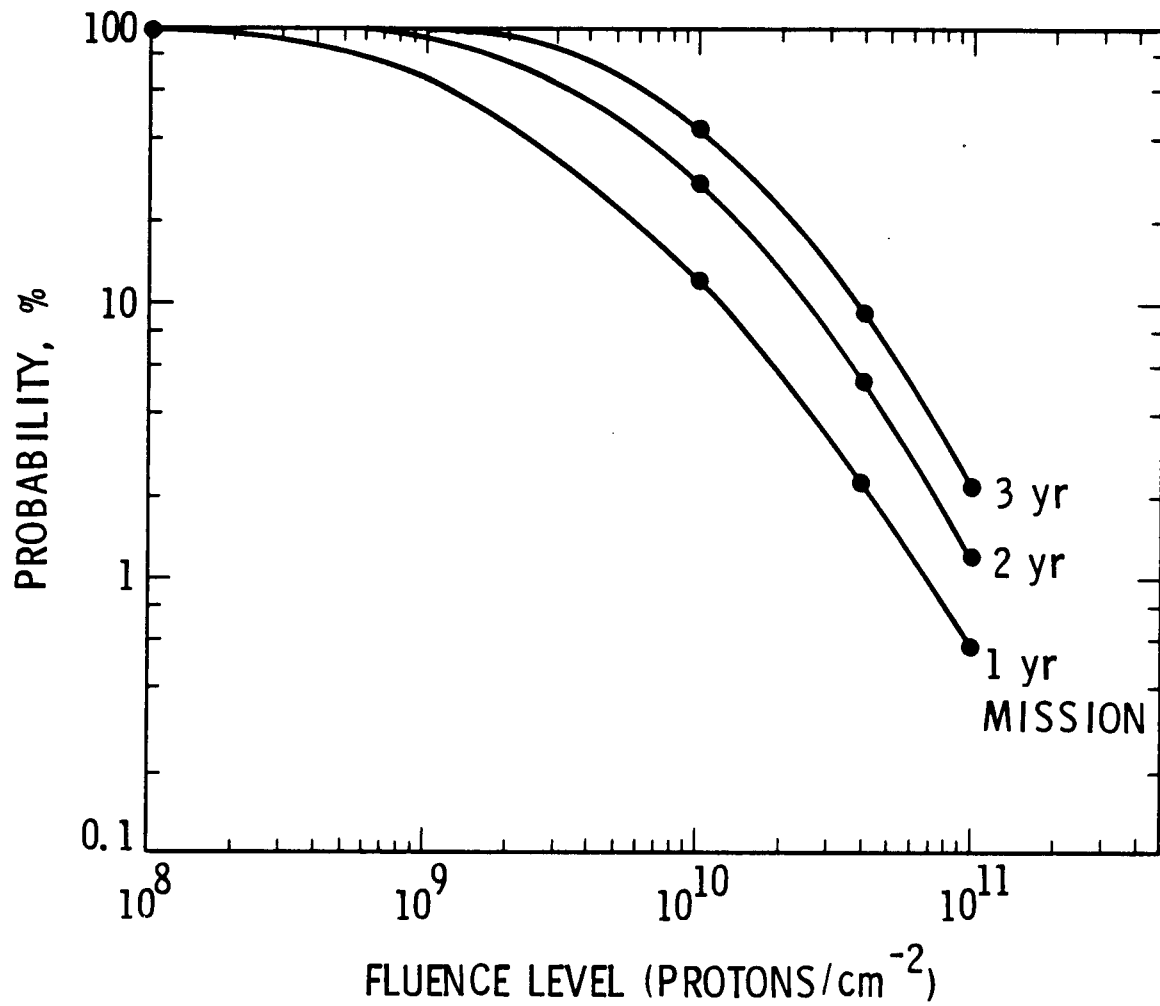


Fig 4 The probability of exceeding selected fluences for different mission lengths for proton energies >10 MeV.